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Deceleration of $\bar{p}$ in the Booster

A.G. Ruggiero

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Introduction

A computer program has been written for the simulation of the deceleration of antiprotons in the Booster. This computer study was directed to investigate the largest beam area (bunch width and height) that could be decelerated with the presently available RF system versus parameters like: injection momentum, transition momentum and Booster ramp speed.

Each computer run simulates turn after turn the motion of 104 "particles" which initially, prior to deceleration, are uniformly distributed along the perimeter of an up-right ellipse in the (ϕ-$\Delta p/p$) phase space: ϕ being the phase angle displacement in RF radians and $\Delta p/p$ the relative momentum deviation. The two axis of the ellipse are assigned for each run and made eventually to change from run to run.

Only one cavity is assumed to be located in the Booster. The RF voltage program is assigned in advance and for computing reasons approximated by the curve shown in Fig. 1. The acceleration period is always assumed to be 33.333 msec and the voltage program adopted is independent of the cycle top momentum p_f. For ordinary cycles this is 8.9 GeV/c but we also considered 6.0 GeV/c and 4.3 GeV/c. The Booster cycle is then given by the following equation for the reference momentum

$$p = \frac{p_f+p_i}{2} - \frac{p_f-p_i}{2} \cos 30\pi\, t_{sec} \qquad (1)$$

where p_i = 0.645 GeV/c. The synchronous phase ϕ_s is calculated from the assigned voltage program and (1).

Each particle is then applied a series of iterations. At the n-th iterations

$$\left(\frac{\Delta p}{p}\right)_{n+1} = \left(\frac{\Delta p}{p}\right)_n \frac{p_n}{p_{n+1}} + \left(\frac{eV}{\beta pc}\right)_n \left[\sin(\phi_n+\phi_s)-\sin\phi_s\right] \qquad (2)$$

$$\phi_{n+1} = \phi_n - 2\pi h\left(\frac{\Delta p}{p}\right)_{n+1} \left[\eta_n + \left(\frac{\alpha_2}{\gamma_T^2} + \frac{3}{2}\frac{\beta^2}{\gamma^2} + \frac{3}{2}\frac{\eta}{\gamma_T^2}\right)_n \left(\frac{\Delta p}{p}\right)_{n+1}\right] \qquad (3)$$

where h is the harmonic number, γ_T the ratio of the transition energy to the rest energy,

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2}$$

and α_2 is a coefficient which depends on the profile of the Booster magnets.[1] We take $\alpha_2 = 0.843$. Observe that in (3) we have calculated also the quadratic contribution of the momentum deviation to the revolution frequency.[1]

The simulation is stopped once the lowest momentum of 0.645 GeV/c is reached.

The program has the feature to count the particles that are "lost" and also to give an approximate estimate of the bunch area.

Discussion of the Results

The results are shown in Tables I, II, III and IV. In the first two tables the initial bunch length is taken to be ±0.2 rad which would correspond roughly to the bunch area of 0.05 eV·s. In this case the largest momentum spread that can be safely accelerated is between 0.10 and 0.13 percent in the ordinary ramp, and between 0.20 and 0.25 percent if the transition energy is shifted above the injection value (p_T = 6.2 GeV/c). Shifting the transition energy to exactly injection causes considerable beam losses also for an initial spread of 0.10%. It seems also that lowering the ramp from 8.9 GeV/c to 6.0 GeV/c does not benefit much.

In Table II we show the results for the injection momentum value of 4.3 GeV/c. For a typical ramp the captured momentum spread is between 0.15 and 0.20 percent, a considerable increase. No improvement is obtained by lowering the ramp to 4.3 GeV/c. And the transmission gets worse when the transition energy is lowered.

Thus it seems that the most advantageous situation for an initial bunch spread of ±0.2 rad is given by an ordinary ramp to 8.9 GeV/c, with a transition momentum jump to 6.2 GeV/c and injection on the fly at 6.0 GeV/c. Injection at 4.3 GeV/c does not yield significant improvement because of the reduction of the $p\bar{p}$-yield at the target.

In Table III we show the results for an initial bunch spread of ±0.5 rad. As it is shown there even for a momentum spread as small as 0.05 percent there is a beam loss. Suspecting that this is then caused by a too large bunch length, we computed several more cases all with zero initial momentum spread and different length. The results are shown in Table IV. We notice that the transition jump does not cause any improvement for longer bunches. In an ordinary cycle the largest spread that can be decelerated is around ±0.3 rad. For lower injection momentum (4.3 GeV/c) this increases to around ±0.5 rad.

In conclusion it seems to us that the deceleration of $\bar{p}$ in the Booster is more sensitive to the initial bunch length, and that only after this is minimized it could be advantageous to raise the transition energy. But in no case the ramp should be lowered, and the higher injection momentum (6.0 GeV/c, h = 85) is desirable.

Inspecting the computer output which displays the beam bunch in the phase space every 500 turns, we noticed that whenever there is a loss this occurs toward the end of the cycle, approaching lower momenta. This is obviously due to a limitation of the bucket area which could be overcome only with considerable RF voltage increase. We also found that it could make sense to take a "matched" initial distribution provided during the deceleration there is no "transition crossing". A matched solution would correspond also to a minimum bunch dilution as one can see from Table I. On the other side crossing the transition in the Booster occurs too fast and the process is not adiabatic enough.

Reference

1. W.W. Lee, TM-333, Fermilab, December 1971

Table I. $P_{inj.} = 6.0$ GeV/c   h = 85 $\Delta\phi = \pm 0.2$ rad

P_{ramp} GeV/c	$P_{trans.}$ GeV/c	$(\Delta p/p)_{inj.}$ ±‰	$(\Delta p/p)_{trans.}$ ±‰	$(\Delta p/p)_{200\ MeV}$ ±‰	Loss %	Dilution
8.9	5.2	1.0	2.4	1.9	-	1.8
		1.3	2.9	-	14	-
		1.5	3.2	-	25	-
	6.0	1.0	-	-	38	-
		1.3	-	-	43	-
		1.5	-	-	40	-
	6.2	1.0	-	2.1	-	2.2
		1.3	-	2.1	-	1.7
		1.5	-	2.1	-	1.5
		2.0	-	2.2	-	1.2
		2.5	-	-	51	-
6.0	5.2	1.3	2.9	2.5	-	2.7
		1.5	3.0	-	23	-
		1.8	4.7	-	51	-
	6.0	1.0	-	-	71	-
		1.3	-	-	71	-
		1.5	-	-	73	-
	6.2	1.5	-	1.9	-	1.2
		1.8	-	2.1	-	1.2
		2.0	-	2.3	-	1.4
		2.5	-	-	45	-

Table II. $P_{inj.} = 4.3$ GeV/c h = 86 $\Delta\phi = \pm 0.2$ rad

P_{ramp} GeV/c	$P_{trans.}$ GeV/c	$(\Delta p/p)_{inj.}$ ±‰	$(\Delta p/p)_{trans.}$ ±‰	$(\Delta p/p)_{200\ MeV}$ ±‰	Loss %	Dilution
8.9	5.2	1.0	-	1.5	-	1.5
		1.3	-	1.9	-	2.0
		1.5	-	2.2	-	2.4
		2.0	-	-	40	-
	4.3	1.0	-	-	11	-
		1.3	-	-	17	-
		1.5	-	-	15	-
4.3	5.2	1.0	-	1.6	-	1.6
		1.3	-	2.0	-	2.1
		1.5	-	2.3	-	2.6
		2.0	-	-	42	-
	4.3	1.0	-	-	73	-
		1.3	-	-	73	-
		1.5	-	-	75	-

Table III. $P_{inj} = 6.0$ GeV/c $h = 85$ $\Delta\phi = \pm 0.5$ rad

P_{ramp} GeV/c	$P_{trans.}$ GeV/c	$(\Delta p/p)_{inj.}$ ±‰	$(\Delta p/p)_{trans.}$ ±‰	$(\Delta p/p)_{200\ MeV}$ ±‰	Loss %	Dilution
8.9	5.2	0.5	4.2	-	48	-
		1.0	4.3	-	56	-
		1.5	4.3	-	78	-
	6.2	0.5	-	-	67	-
		1.0	-	-	68	-
		1.5	-	-	74	-
6.0	5.2	0.5	6.2	-	37	-
		1.0	6.4	-	46	-
		1.5	6.6	-	66	-
	6.2	0.5	-	-	63	-
		1.0	-	-	63	-
		1.5	-	-	69	-

<u>Table IV</u>. $(\Delta p/p)_{init.} = 0$

$P_{inj.}$ GeV/c	P_{ramp} GeV/c	$P_{trans.}$ GeV/c	$\Delta\theta$ ± rad	$(\Delta p/p)_{trans.}$ ‰	$(\Delta p/p)_{200\ MeV}$ ‰	Loss %
6.0	8.9	5.2	0.3	0.9	-	5
(h=85)			0.4	2.1	-	24
			0.5	4.2	-	46
		6.2	0.3	-	-	33
			0.4	-	-	56
			0.5	-	-	65
	6.0	5.2	0.3	3.6	2.1	-
			0.4	5.2	-	22
			0.5	6.1	-	28
		6.2	0.3	-	-	21
			0.4	-	-	48
			0.5	-	-	60
4.3	8.9	5.2	0.3	-	1.5	-
(h=86)			0.4	-	2.3	-
			0.5	-	-	18
	4.3	5.2	0.3	-	1.4	-
			0.4	-	2.0	-
			0.5	-	2.3	-
			0.6	-	-	25

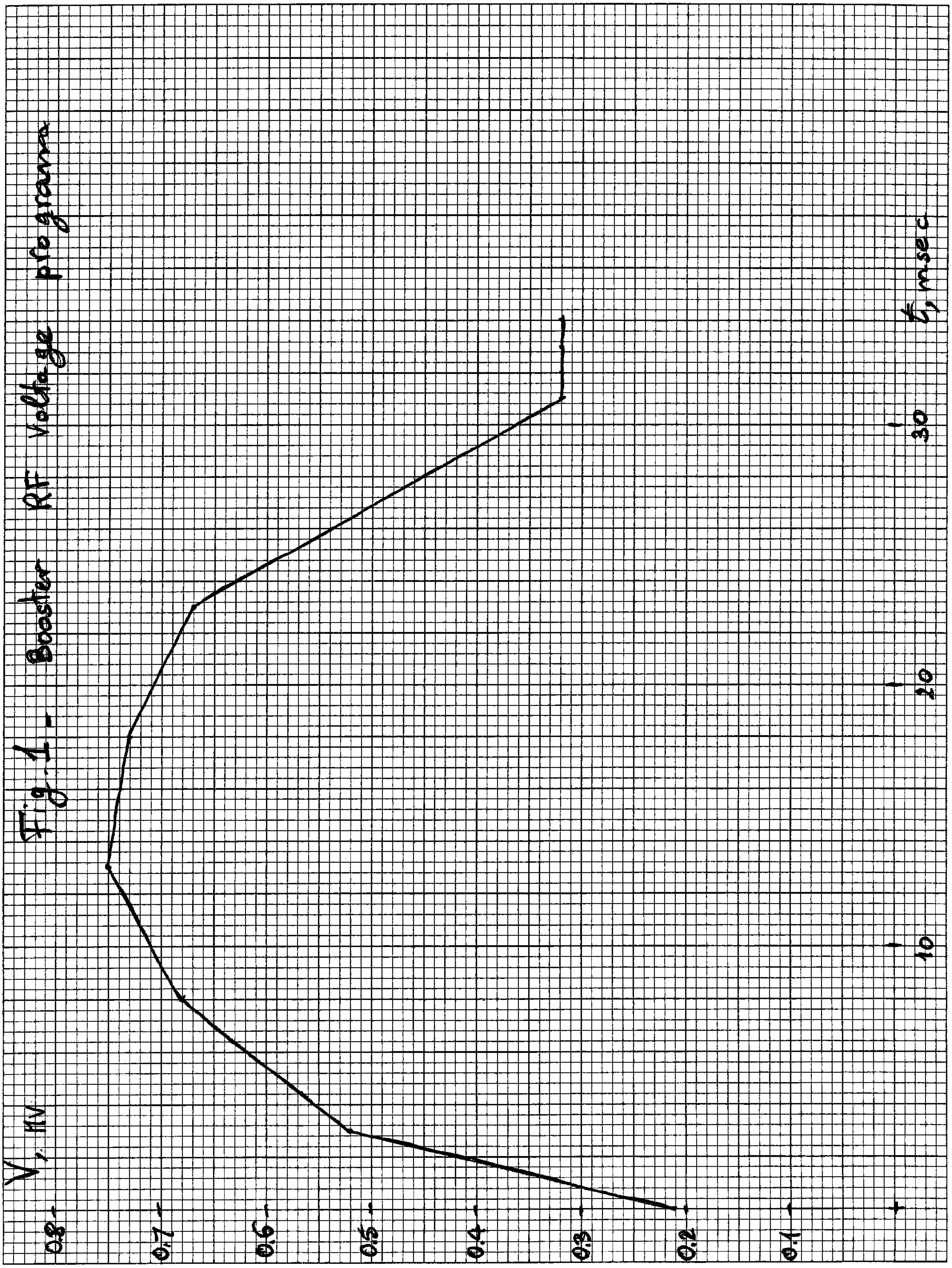

Fig. 1 - Booster RF Voltage program